LIFETIME OF ASYMMETRIC COLLIDING BEAMS IN THE LHC

J.M. Jowett, R. Alemany-Fernandez, M.A. Jebramcik*, T. Mertens†, M. Schaumann,
CERN, Geneva, Switzerland

Abstract

In the 2013 proton-nucleus (p-Pb) run of the LHC, the lifetime of the lead beam was significantly shorter than could be accounted for by luminosity burn-off. These effects were observed at a lower level in 2016 and studied in more detail. The beams were not only asymmetric but the differences in the bunch filling schemes between protons and Pb nuclei led to a wide variety of beam-beam interaction sequences in the bunch trains. The colliding bunches were also of different sizes. We present an analysis of the data and an interpretation in terms of theoretical models.

INTRODUCTION

As previously in 2013 [1], all four main detectors of the LHC were taking p-Pb collisions during the heavy-ion run of 2016 [2]. Bunches can be injected into the LHC in every 10th of the 35640 RF buckets, a spacing conventionally referred to as "25 ns" although it is slightly less. The minimum spacing between Pb bunches coming from the injectors [3] is presently 100 ns. The proton beams are created with a similar basic spacing although the trains injected into the LHC contain other spacings and the gaps between trains in the LHC can be any multiple of 25 ns.

The 4 experimental interactions points (IPs) are distributed along the circumference, C, of the LHC. All bunch pairs colliding at ATLAS (IP1, at $s_{\text{IP1}} = 0$) will also collide at the diametrically opposite CMS (IP5, at $s_{\text{IP5}} = C/2$). If the filling scheme is four-fold symmetric (filling by quadrants) collisions will also occur at ALICE (IP2, $s_{\text{IP2}} = C/8$). However this symmetry must be broken to arrange collisions at LHCb (IP8, $s_{\text{IP8}} = 1039C/1188$). (This is not the case for bunches spaced by 25 ns). Other constraints related to the abort-gap mean that the filling schemes of the two beams are complex and different. Generally the number of collisions in LHCb is smaller than in the other experiments, in keeping with the relative luminosity requirements.

In this paper we focus on the Pb beam, whose rapid burn-off usually determines the length of a fill. The intensity of the proton beam, which barely changes during a fill, is also simulated because its emittances change.

In the sense of [4] (and ignoring parasitic encounter points), there are 8 beam-beam equivalence classes in the Pb beam, categorising each of the circulating bunches, as indicated in Table 1. The bunch lifetimes differ for each class and may further depend on individual bunch populations N_b. Unlike [4], where both beams were assumed to have the same filling scheme, there is, in general, no simple relationship to classes in the p beam.

* marc.jebramcik@cern.ch
† tom.mertens@cern.ch

Table 1: Beam-beam equivalence classes in the Pb beam with the IPs they collide at. Bunches in class 8 do not collide.

Class	1	2	3	4	5	6	7	8
ATLAS/CMS	•			•	•		•	
ALICE		•		•		•	•	
LHCb			•		•	•	•	

SIMULATION OF BEAM EVOLUTION

Collider Time Evolution

The Collider Time Evolution (CTE) program [5] is used to simulate the slow time evolution (kinetic effects over many turns) of LHC bunches. It starts by generating 6D particle phase-space distributions for a given set of bunches and their initial conditions in each beam. These distributions are updated on each simulation turn by sequentially applying different physical processes to them. In the present application, these include: synchrotron motion, betatron motion, radiation damping, intra-beam scattering (IBS) and collisions. The IBS routine uses a simplification [6] to reduce computation times (see [7] for a comparison of several IBS models implemented in CTE). A recent update of CTE [8] simulates colliding particle beams of different species. The updated collision routine automatically determines the collision pattern for each bunch in each beam (where it collides, with which bunch and in which order) and takes into account the crossing angles, β^* and, possibly, luminosity levelling at the different IPs. Particle losses in a CTE simulation originate from de-bunching (IBS-driven losses from the RF bucket) and luminosity (momentum and betatron losses can be introduced by activating the collimation routine but this was not used here).

Alternatively, one can solve differential equations for moments of the bunch distributions (see below). Both approaches are compared with data from LHC fill 5549. The CTE simulations were run twice: with zero and full betatron coupling of the IBS growth rates between the two transverse planes.

Ordinary Differential Equation Model

With familiar assumptions, the evolution of a single bunch can be described by 4 ordinary differential equations (ODEs)

$$\begin{aligned}
\dot{\epsilon}_{n,u} &= 2\epsilon_{n,u}\left(\alpha_{\text{IBS},u}(N_b,\epsilon_{n,x},\epsilon_{n,y},\sigma_z) - \alpha_{\text{r},u}\right) \ (u = x, y) \\
\dot{\sigma}_z &= \sigma_z\left(\alpha_{\text{IBS},z}(N_b,\epsilon_{n,x},\epsilon_{n,y},\sigma_z) - \alpha_{\text{r},z}\right) \\
\dot{N}_b &= -\sum_{i\in\text{IPs}} \sigma_{\text{inel}}\mathcal{L}_i(N_b,\epsilon_{n,x},\epsilon_{n,y},\widetilde{\mathbf{N}}_b,\widetilde{\epsilon}_{n,x},\widetilde{\epsilon}_{n,y}) - N_b\alpha_X
\end{aligned}$$

where $\epsilon_{n,u}$ are the normalised transverse emittances in each plane, σ_z the longitudinal RMS bunch length and N_b the

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number of particles within the bunch. For the transverse and longitudinal evolution, only IBS and radiation damping are considered, using the growth and damping rates $\alpha_{\mathrm{IBS},x,y,z}$ and $\alpha_{\mathrm{rad},x,y,z}$. The change of the bunch intensity depends on the losses due to the luminosity production, $\sigma_{\mathrm{inel}}\mathcal{L}$ (luminosity burn-off), which depends not only on the total inelastic cross-section $\sigma_{\mathrm{inel}} = 2.06$ b [9] and the parameters of the bunch itself, but also on the properties $\widetilde{\mathbf{N}}_b$, $\widetilde{\epsilon}_{n,x}$ and $\widetilde{\epsilon}_{n,y}$ of a subset of all the bunches in the other beam, via the filling scheme-dependent luminosity function $\mathcal{L}_i$ at IP i. Additional losses, due to other effects like residual-gas scattering and de-bunching, are subsumed in the term $N_b\alpha_X$.

In the ODEs, a high-energy approximation [10] of the calculation of the IBS growth rates $\alpha_{\mathrm{IBS},u}$ ($u \in x, y, z$) of [11] is used. For simplicity, the formulas of [10] are applied using average values of the optical functions around the ring.

The underlying losses from effects other than luminosity burn-off are accounted for by extracting the average loss rate of the non-colliding bunches (class 8), i.e., $\alpha_X = \left\langle -\dot{N}_b/N_b \right\rangle_{\text{class 8}}$.

Here and in the following, we refer to a *corrected ODE model*. This model includes additional loss rates, which differ for each IP and might depend on the optics settings like crossing angle or β^* at the IP, to achieve better agreement with the data. In addition, this model also includes a scaling factor of the IBS growth rates as both CTE and the ODE model overestimate these.

FILL 5549 AT 6.5 Z TeV

Fill 5549 had a beam energy of 6.5 Z TeV, with Pb ions in Beam 1 and protons in Beam 2. Both the ODE model and CTE simulations gave very good agreement with data for protons, but for ions we observe some effects that are not understood within the present models. These effects depend on the beam-beam class the bunch belongs to. We studied several bunches from different beam-beam classes but, for reasons of space, only two examples of extreme Pb bunches are presented: bunch 5, which collides only in IP8 (class 3), and bunch 73, which collides in IP1, IP5 and IP8 (class 7).

Comparing the evolution of bunch 5 with that of bunch 73 in Beam 1 in Figs. 1-5, illustrates these effects. Both simulations seem to agree well for the intensity evolution of bunch 5, while there is a clear discrepancy for bunch 73. Only a corrected ODE simulation seems to get close to the measured intensity evolution: the simulated intensity decay is slower than the measured data, although the simulated luminosity exceeds the luminosity recorded by the experiments. Hence, additional IP-dependent loss rates are introduced to achieve better agreement and might give an indication of the source of these losses. The additional losses are assumed to be of exponential nature, i.e., $\dot{N}_b = -\alpha_{\mathrm{corr}}N_b$. The fitted values of α_{corr} are listed for the Pb beam in Table 2 for each IP. Further investigation may reveal their dependence on the crossing angles and β^* values. In the case of protons, the corrections are $< 10^{-3}\,\mathrm{h}^{-1}$ and therefore negligible.

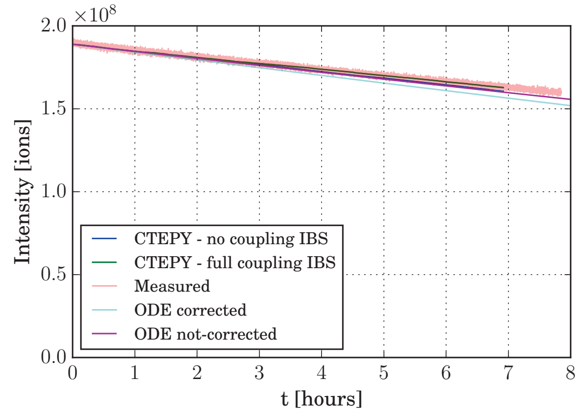

Figure 1: Fill 5549; Intensity evolution bunch 5.

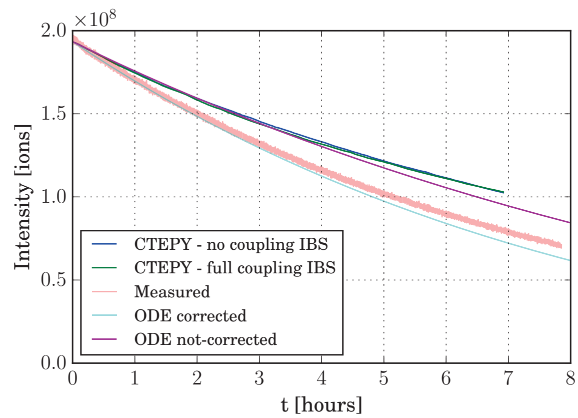

Figure 2: Fill 5549; Intensity evolution bunch 73.

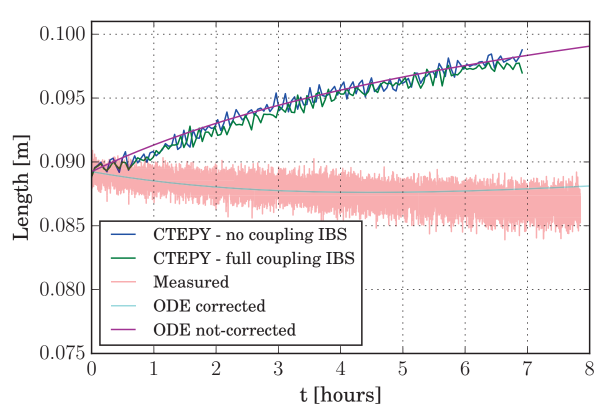

Figure 3: Fill 5549; Bunch length evolution bunch 5.

Table 2: IP configurations during Fill 5549 and additional loss rate estimates.

	ATLAS/CMS	ALICE	LHCb
No. of collisions	405	236	251
β^* [m]	0.6	2.0	1.5
$\theta/2$ [μrad]	140	63	325
$(1/\alpha_{\mathrm{corr,Pb}})$ [h]	64	34	420

Similarly, the simulations overestimate the bunch lengths. Only the plot for bunch 5 is shown in Fig. 3, but bunch 73 shows similar behaviour. Assuming bunch length growth is mainly caused by IBS, which is an intensity driven effect, extra losses not included in the simulations could explain the observed discrepancy. In order to achieve a better agreement, the IBS growth rates were scaled down by forty percent within the corrected ODE model. One part of this correction comes due to the fact that the IBS model (used in the ODE simulations) is based on averaged optical functions only. Most of the assumptions made regarding the bunch length are at least partially valid for the transverse emittances, where similar behaviour to the bunch length evolution is observed (see Fig. 4 as an example).

Moving to the luminosity evolution of bunch 73 (bunch 5 only collides in IP8, where data was not understood well enough to make a reliable comparison at the time of writing), we found that the simulations over-estimate the initial luminosity in IP1 and (less pronounced) in IP5, see Fig. 5. This could again be explained by intensity losses not accounted for in the simulations.

The fact that bunches belong to different collision classes and the occurrence of not understood additional losses lead to large differences in bunch lifetimes. Figure 6 shows the measured lifetimes for the different bunches of the Pb beam for fill 5449 (black dots). Bunches colliding in multiple IPs clearly have a shorter lifetime than those colliding in a few IPs or are non-colliding.

A repeating variation with increasing bunch number, broadly reflecting the membership of the beam-beam classes, can be observed in Fig. 6. The frequency of this oscillation is consistent with the position of injected bunch trains and within each train, it follows the initial intensity structure of such a train. This demonstrates that both collision class and initial intensity are important factors for the bunch lifetimes. In addition to the lifetimes extracted from the data, Fig. 6 also displays the lifetimes, which are extracted from the corrected ODE model (red dots). Using the corrections discussed above the results are in excellent agreement between corrected ODE simulation and data, even the variation of the lifetime along the bunch trains are reproduced.

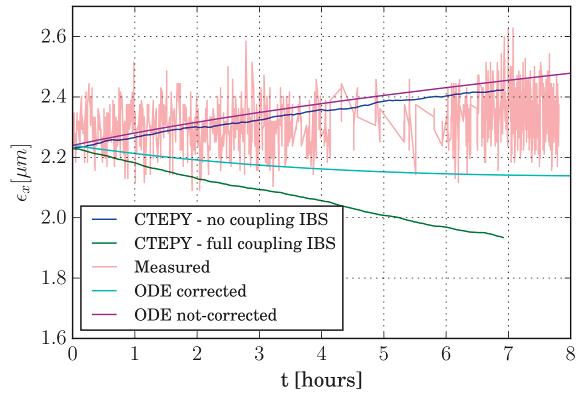

Figure 4: Fill 5549; Horizontal (normalized) emittance evolution bunch 5.

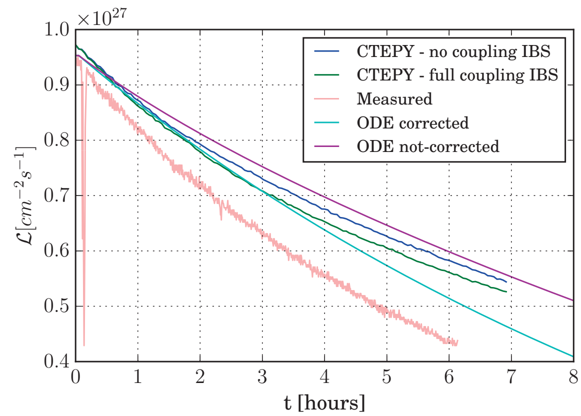

Figure 5: Fill 5549; Luminosity at IP5 for bunch 73.

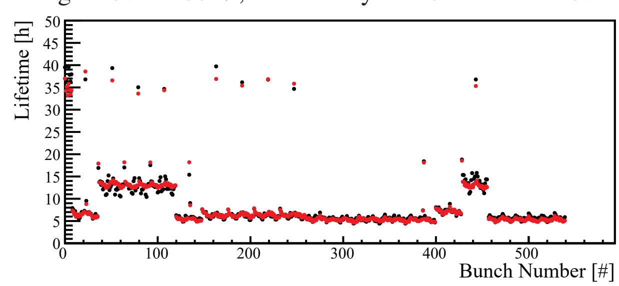

Figure 6: Fill 5549: bunch lifetimes along the train, from measured data (black) and the corrected ODE model (red).

CONCLUSIONS

We presented a first analysis of selected data from LHC p-Pb fill 5549 with variants of two different simulation approaches in order to study the observed bunch lifetimes in the Pb beam. Our investigation showed that the bunch lifetimes mainly depend on the bunches' collision classes and initial intensities. The presented data and simulations show the presence of additional losses that are not yet understood and affect the bunch lifetimes. A comparison with the corrected ODE simulations seems to indicate that these losses are, at least partially, of exponential nature. Further analysis is required to understand the source of these losses although it can be hypothesised that they are related to collisions of bunches of unequal size and population and nearby parasitic encounters in the very complex situation of the p-Pb fills. By using the corrected IBS model, the complex bunch lifetime patterns along the bunch train are reproducible and an excellent agreement with the data is achieved. The fills at $E_b = 4\,Z$ TeV [2], in which the beam losses were not dominated by luminosity burn-off, are beyond the scope of this paper and will require further analysis of another complex colliding system.

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